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13. ABSTRACT (Maximum 200 words)

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A planar array for the generation of evanescent waves

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Wavenumber-frequency calibration of underwater, planar, receiving arrays requires the ability to generate single-wavenumber pressure fields over the surface of the array. When the wavenumber-frequency region of interest is evanescent, transmitting arrays previously constructed have been found to generate fields contaminated with harmonics, acoustic wavenumbers, and nonacoustic wavenumbers from the excitation of antisymmetric Lamb waves. An array that greatly reduces contamination has recently been constructed using a sheet of polyvinylidene fluoride (PVDF) with independent rectangular electrode stripes. The array operates in the frequency range of 500 Hz to 2 kHz and generates evanescent waves with phase speeds between 30 and 150 m/s. Contamination due to the excitation of antisymmetric Lamb waves is eliminated by shifting the phase speed of the Lamb wave out of the region of interest. This is accomplished by bonding the thin sheet of PVDF directly to a thick plate of LEXAN. Contamination from harmonics and acoustic wavenumbers is eliminated by driving the electrode stripes with suitably chosen shading coefficients generated by a simple-source numerical algorithm. Measured pressure fields and phase velocities compare favorably with numerical calculations.

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INTRODUCTION

The use of sonar receiving arrays underwater on high-speed platforms involves operating in the presence of significant levels of flow noise. The successful development of such arrays requires that the impact of flow noise on array performance be greatly reduced. For the case of planar sonar arrays, the spatial structure of the flow field can be resolved into a two-dimensional wavenumber spectrum in the plane of the array. In the flow direction the spectrum peaks at the hydrodynamic wavenumber $k \simeq \omega/(0.6U)$, where ω is the angular frequency and U is the platform speed,[1] and is coherent over relatively long distances. In the lateral direction the coherence length is much shorter than that in the flow direction.

The sonar array performance can be improved by discriminating against the nonacoustic wavenumbers in the flow noise spectrum. This can be accomplished by using hydrophones with large lateral dimensions to sum the lateral component of the flow noise incoherently and by using dimensions in the flow direction which exceed the nonacoustic wavelength. An additional degree of signal-to-noise ratio enhancement can be obtained by separating the array from the flow field with the use of an acoustically transparent decoupling material. Both of these methods will be required to suppress the low wavenumber portion of the flow noise spectrum. In order to optimize the design, one must be able to ascertain the performance of decoupling materials and designs (i.e., to understand the interaction of evanescent waves with various materials) and to obtain wavenumber-frequency calibrations of transducer modules and arrays. The most straightforward means of accomplishing both of these requirements is to construct an array that is capable of producing a single-wavenumber, evanescent pressure field over a specified planar region.

An array that is both acoustically transparent and capable of generating a single-wavenumber, evanescent pressure field can be placed close to a receiving array. The wavenumber-frequency response of the receiving array can then be obtained directly without distortion due to reflections from the generating array. The generating array can also be used to investigate the interaction of evanescent pressure fields with various materials and compliant surfaces.

Powers and Sherman[2] were the first to construct an evanescent wave generating array for determining the wavenumber-frequency response of hydrophones. They constructed a small array of air-backed cylindrical polyvinylidene fluoride (PVDF) transducer elements spaced 0.34 cm apart that was operated in the frequency range of 1 to 10 kHz. The elements were driven in air with identical amplitudes and with neighboring elements in phase opposition, thus, the primary wavenumber generated by the array was fixed by the element spacing. The experimental results indicated that evanescent waves with the desired nonacoustic wavenumber could be produced. However, undesired acoustic wavenumbers and harmonics of the nonacoustic wavenumber were also generated that contaminated the desired pressure field to an unusable level. More recently,[3] an array was constructed using a sheet of lead-titanate impregnated neoprene with independent electrode stripes. This array was tested underwater in the frequency range of 500 Hz to 2 kHz and was also found to generate evanescent waves. However, the pressure field was contaminated with acoustic wavenumbers and nonacoustic wavenumbers from the excitation of an antisymmetric Lamb wave with a phase velocity close to that of the desired evanescent wave.

In this paper we describe a different approach to constructing an evanescent wave generating array using a sheet

042

of PVDF and we present experimental results obtained with a small test array. The first section describes the design and construction of the array such that it is both acoustically transparent and eliminates contamination due to the excitation of antisymmetric Lamb waves. The second section describes the theory for the generation of the complex shading coefficients used to obtain the desired evanescent pressure fields. The third section presents measurements of the pressure fields and phase velocities generated by the array and compares these with numerical calculations. The paper concludes with a discussion of the results.

I. ARRAY CONSTRUCTION

An ideal evanescent wave generating array is illustrated in Fig. 1. The source is an acoustically transparent infinite plane surface immersed in an infinite fluid. The surface of the array has a sinusoidal acceleration distribution propagating in the positive x direction with an adjustable structural wavelength λ_s that is independent of the driving frequency ω. If it was possible to construct this ideal evanescent wave generating array, and assuming that the structural wavenumber k_s was chosen larger than the fluid wavenumber k_a ($\equiv \omega/c_0$, where c_0 is the free-field sound speed in the fluid), the resulting pressure field in the fluid would be given by

$$p(x,z,t) = \rho\ddot{w}(k_s^2 - k_a^2)^{-1/2} \exp[-(k_s^2 - k_a^2)^{-1/2} z] \times \exp[i(k_s x - \omega t)], \quad (1)$$

where ρ is the fluid density and $\ddot{w}$ is the acceleration. This is a pure (single wavenumber) evanescent plane wave that decays exponentially away from the surface of the array. Calibration of a hydrophone would simply consist of positioning it close to the array and measuring its output voltage. The acoustic transparency of the array would eliminate any problem of standing waves developing between the array and the hydrophone that would interfere with the calibration.

Unfortunately, the ideal evanescent wave generating array is not practical. We consider instead an approximation consisting of a finite version with an acceleration distribution composed of discrete steps. Both the finite size and the discrete steps impose limitations and difficulties for a practical evanescent wave generator.

Our design of such an array for generating evanescent waves is based upon using a sheet of PVDF for the active element. One side of the sheet contains a large number of independently controlled copper-electrode stripes and the other side a solid copper ground plane. The use of PVDF greatly reduces the weight of the array, helps in allowing the array to be acoustically transparent, and simplifies construction. The large number of stripes allows one to implement a discrete version of the acceleration distribution needed to generate uncontaminated evanescent waves.

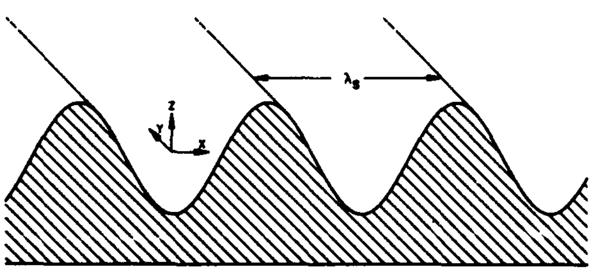

FIG. 1. Ideal evanescent wave generating array with sinusoidal surface acceleration of adjustable wavelength λ_s.

Prior to designing and constructing the array described in this paper several small test arrays have been investigated. Each of these arrays utilized a 0.05-cm-thick sheet of PVDF 12.7 cm × 12.7 cm, similar to that shown in Fig. 2, having 20 rectangular electrode stripes. Various arrays were constructed with the sheet of PVDF either mounted on a thin, 0.32-cm-thick sheet of plastic to maintain planar geometry or potted in a 1-cm-thick layer of material which has an acoustic impedance equal to that of water. These arrays were used in an attempt to generate evanescent waves in water with phase speeds in the 30- to 150-m/s range. However, in each case an antisymmetric Lamb wave was strongly excited in the array.

The antisymmetric Lamb wave is a highly dispersive flexural wave[4] that has a low phase speed at low frequency and is thus easily excited in attempting to generate low-phase-speed evanescent waves with the array. These Lamb waves contaminate the wavenumber spectrum of the pressure field and are particularly troublesome when resonant along the width of the array. There are, however, two simple means of eliminating their excitation. The first is to slice the PVDF along the stripes to eliminate lateral coupling along the sheet and then embed the sheet in a heavily damped material that does not support the propagation of flexural waves. The second method, and that chosen for the array design reported in this paper, is to bond the PVDF sheet directly to a thick plate of rigid material that has an acoustic impedance reasonably close to that of water (e.g., LEXAN has a specific gravity of 1.2 and a sound speed of 2200 m/s). The plate is used to shift the phase speed of the antisymmetric Lamb wave, which has a phase speed that scales as a frequency-thickness product, to a value much higher than the phase speed of evanescent waves that we desire to generate. This eliminates the phase matching that was responsible for the excitation of the Lamb wave.

The PVDF sheet used in the array described in this paper was bonded to a 2.5-cm-thick piece of LEXAN. The LEXAN is thick enough to shift the phase speed of the antisymmetric Lamb wave to a value well above 150 m/s in the 500-Hz to 2-kHz operating frequency range of the array while remaining thin enough to be acoustically transparent in this region. The PVDF sheet is bonded with the side containing the electrode stripes next to the LEXAN. This configuration prevents electromagnetic coupling between the evanescent wave generating array and the hydrophone being calibrated by placing the ground plane of the PVDF next to the fluid interface. While this configuration is standard hydrophone design, it is a very important consideration in this case due to the structure of the field. The evanescent waves decay rapidly in the fluid and the generating array must be placed close to the hydrophone being calibrated (e.g., the evanescent field decays at the rate of 36 dB per centimeter for

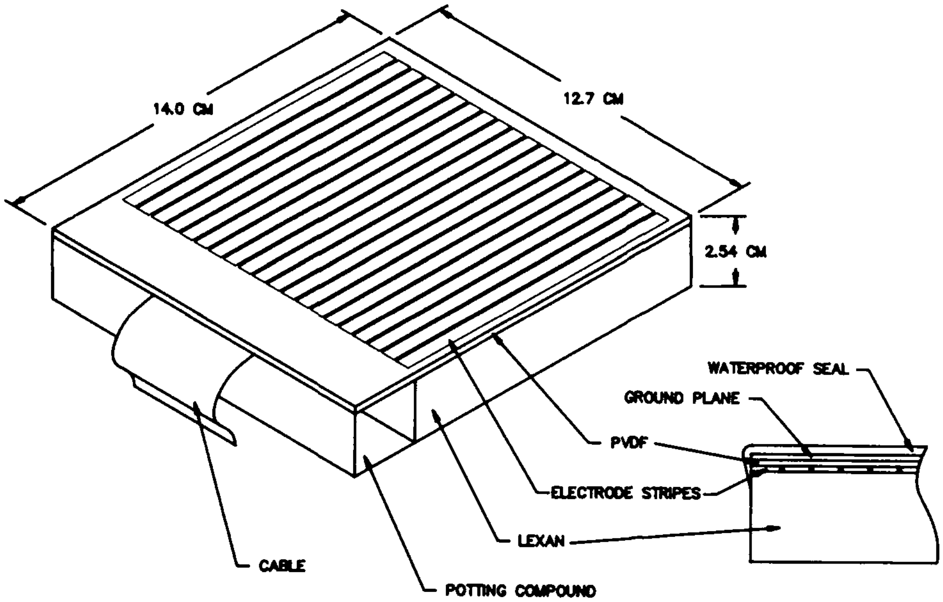

FIG. 2. Evanescent wave generating array composed of a sheet of electroded PVDF bonded to a 1-in.-thick piece of LEXAN.

a phase speed of 30 m/s and a frequency of 2 kHz).

Each of the 20 electrode stripes on the PVDF was 0.56 cm wide and 10.8 cm long and they were separated from each other by a 0.076-cm gap. These dimensions were chosen arbitrarily for the 0.05-cm-thick sheet of PVDF used in constructing this array. The width of the stripes along with the required minimum number of stripes per wavelength (a value determined experimentally in this investigation as described later) will determine the shortest wavelength that the array can generate. If it is required that very short wavelengths be generated, the stripes must be made narrower. However, the width of the stripe should not be made too narrow in comparison with the thickness of the PVDF as this will result in large capacitive coupling between adjacent stripes through their fringing fields. This capacitive coupling will adversely impact the array performance by changing the effective voltage drive of each stripe.

The voltage drive for each of the electrode stripes was independently controlled with its own power amplifier. All of the power amplifiers were computer controlled and driven with individual digital-to-analog converters operating from the same clock. A computer program set the frequency of operation. In addition, the desired relative amplitudes and phases of the voltage drives for each of the stripes, as determined by a set of computed complex shading coefficients, were inserted into the computer program.

II. SHADING COEFFICIENTS

The transfer function of an array of acoustic sources relates the shading coefficients (complex numbers representing amplitude and phase which are used to modify the voltage drives of the sources) to the pressure field generated by the array. There are two methods for generating the transfer function. The first method involves experimentally determining the elements of a transfer matrix and the second method determines the elements numerically.

It has been demonstrated that, in general, the elements of a transfer matrix can be obtained at a particular frequency by measuring the acoustic field produced by each source, or in this case stripe, operating individually.[5] The only requirements for using the transfer matrix are that the system be linear and that the acoustic field be measured at as many, or more, locations as there are sources. Once the transfer matrix has been obtained its inverse relates the desired pressure field, at the measurement locations, to the necessary shading coefficients with which the array should be operated. This procedure is very useful in that it incorporates unknown boundaries and boundary conditions, if these are present; it does not require knowledge of source calibrations; and it includes effects of the medium (e.g., absorption). However, the procedure is time consuming and difficult to implement when a large number of sources are involved.

One of the advantages of constructing an acoustically transparent evanescent wave generating array and of eliminating possible excitation of Lamb waves, is that the stripes and the array as a whole behaves as a simple source. This allows the use of the second method for determining the transfer matrix. In this method the cumbersome measurement procedure is replaced with a numerical algorithm, based upon integrations over simple sources, for generating the elements of the transfer matrix. This method is described in this section and differs from that in Ref. 5 only in the use of the numerical algorithm.

Figure 3 illustrates the geometry used in the numerical procedure. Arbitrarily, using a random number generator, a large number of points are chosen in a plane above the array where the transducer to be calibrated will be placed. Two hundred points were used for the small test array with 20 stripes. The extent of the region in which the points are chosen must be less than the size of the array, leaving approximately a $\frac{1}{2}$ wavelength (of the evanescent wave) border in which the field falls off to zero. The acoustic pressure at the i th point due to the j th stripe being driven with unit amplitude is given by

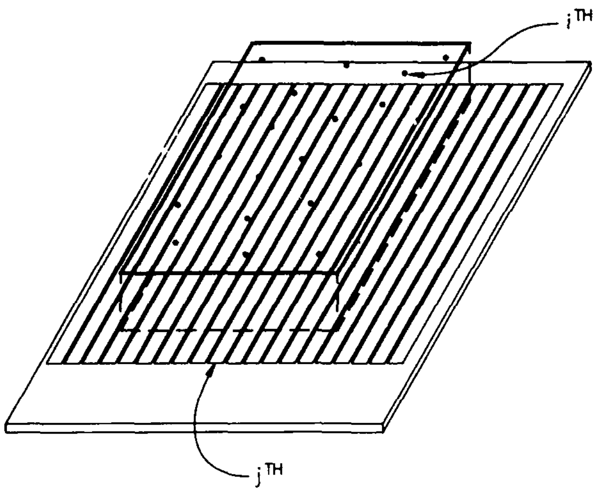

FIG. 3. Geometry used in the numerical algorithm for the generation of shading coefficients.

$$p_{i,j} \equiv M_{ij} = \int_j |r^{-1}(x-x',y-y')| \times \exp[i(k_a|r(x-x',y-y')| - \omega t)]dx'\,dy', \quad (2)$$

where $r(x-x',y-y')$ is a vector from the surface element $dx'\,dy'$ to the field point (x,y), M_{ij} is an element of the transfer matrix, and the integral is over the jth stripe. Upon completion of this calculation for each field point–stripe combination one has constructed a transfer matrix. This transfer matrix may be used to obtain the total acoustic pressure at the ith field point when the stripes are driven with complex shading coefficients D_j. The total acoustic pressure is given by

$$p_i = \sum_j D_j M_{ij} = \sum_j D_j \int_j |r^{-1}(x-x',y-y')| \times \exp[i(k_a|r(x-x',y-y')| - \omega t)]dx'dy', \quad (3)$$

or in matrix notation

$$\mathbf{P} = \mathbf{MD}. \quad (4)$$

Having generated more field points than there are stripes requires that a pseudoinverse technique be used to yield a least-squares solution for the shading coefficients given by

$$\mathbf{D} = (\mathbf{M}'^{*}\mathbf{M})^{-1}\mathbf{M}'^{*}\mathbf{P}, \quad (5)$$

where the vector **P** is the desired pressure field at the field points, which is the evanescent pressure wave in Eq. (1).

The resulting shading coefficients will minimize the least-squares error between the desired pressure field and the calculated field over the specified surface. In general, the algorithm will generate both an evanescent pressure field and additional wavenumbers that correct for the finite aperture and divergence in the field. The least desirable wavenumber is zero which corresponds to an acoustic plane wave propagating in the normal direction to the surface of the array. In order to prevent the generation of this wavenumber we require that the monopole moment of the array be zero in a least-squares manner, which is accomplished by adding an equation to Eq. (4) which sets the sum of the shading coefficients D_j equal to zero. The weighting of the equation, which is added to Eq. (4), will determine how close the sum of the shading coefficients comes to zero. This weighting must be determined empirically as both too large and too small of a value fails to optimize the results.

III. EXPERIMENTAL RESULTS

The array shown in Fig. 2 was mounted in a small water tank, and a Bruel and Kjaer 8103 miniature hydrophone was mounted on a positioner to map the pressure field. The stripes were driven with calculated shading coefficients and the pressure field was mapped 0.63 cm in front of the array with the amplitude and phase recorded by a Nicolet digital oscilloscope.

In Fig. 4 the amplitude of the measured pressure field across the centerline of the array has been compared with the calculated amplitude. The experimental results were obtained with shading coefficients calculated for a frequency of 1 kHz, a phase speed of 70 m/s, and a window width arbitrarily chosen to be 6.0 cm. As is obvious from the results, the agreement is poor. The problem is in the choice of window size.

The wavenumber spectrum of the pressure field being generated is a convolution of the evanescent wavenumber with the wavenumber spectrum of the aperture. In this case, the spectrum of the aperture is essentially that of a square wave. Thus, the wavenumber spectrum being generated is approximately

$$F(k)\sin[(k-k_s)a]/(k-k_s)a, \quad (6)$$

where a is half the width of the window. If the window is not chosen such that Eq. (6) equals zero for the acoustic wavenumber k_a then the algorithm generating the shading coefficients generates a dipole outside the window region. The dipole allows the field to be uniform (i.e., having no x or y dependence) within the window region for a single $z =$ const plane. However, the acoustic field and the evanescent field destructively interfere for all other planes. If the window is

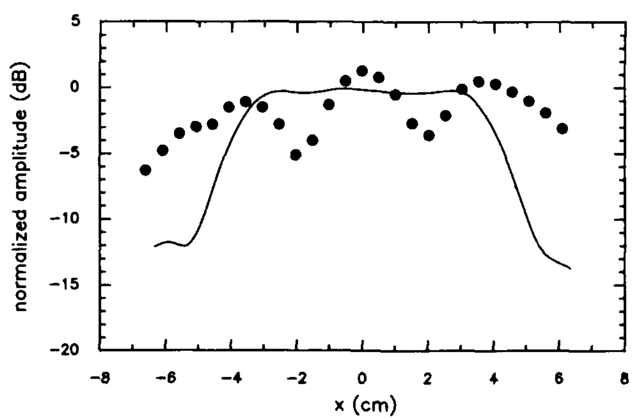

FIG. 4. Comparison of measured pressure amplitude (solid circles) with that calculated by the numerical algorithm (solid line). The data were obtained from measurements across the centerline ($y = 0$) of the array 0.63 cm away from the surface. The array was driven at 1 kHz and was attempting to generate an evanescent wave with a phase speed of 70 m/s across the 6.0-cm-wide window region.

chosen such that Eq. (6) equals zero for the acoustic wavenumber k_a, no dipole field is generated, and the pressure field generated by the array is uniform over a range of z. The field cannot be made uniform for all values of z due to the finite aperture. The various wavenumber components of the spectrum of the aperture function decay in the z direction at different rates. This results in a relative loss of higher wavenumber components with increasing distance in the z direction.

Figure 5 illustrates the results obtained when new shading coefficients are calculated for the example in Fig. 4 with a window width of 7.34 cm. The results agree within ± 0.5 dB over the specified window region. In Fig. 6 the measured relative phase is compared with the calculated phase from the numerical algorithm and with the desired phase. The results are nearly linear over the window region indicating little contamination from undesired wavenumbers and the phase speed is in close agreement with the desired result.

These results are typical of those obtained at other frequencies and phase speeds when at least ten stripes per evanescent wavelength are used and the window width is chosen correctly. Using fewer than ten stripes per wavelength results in a gradual degradation of the generated field for the small test array investigated. This degradation is due to the discrete phase steps used in generating the field that results in high wavenumber components associated with the aperture not being produced accurately and the increased aliasing of high wavenumber aperture components with decreased numbers of stripes per wavelength. It may be possible to use fewer stripes per wavelength with larger arrays.

Although the field of the array is controlled in one dimension only, the pressure field generated is uniform over the window region in both the x and y directions. Figure 7 illustrates the pressure field measured along the centerline of the array, 3.2 cm above the centerline, and compares these with the calculated field. In this example the frequency was 1 kHz, the phase speed was 60.2 m/s, and the window was 6.0 cm. The results indicate that the amplitude is uniform within approximately ± 1.0 dB.

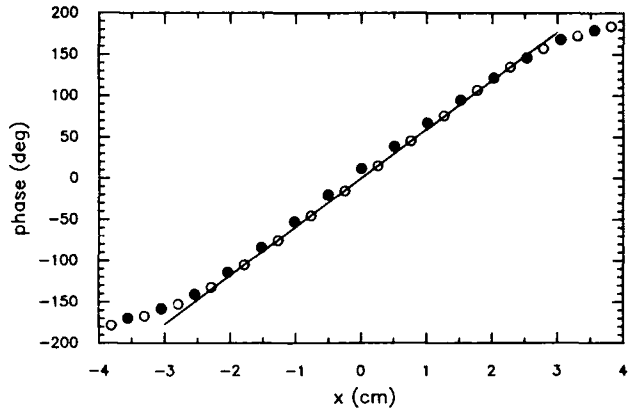

FIG. 6. Comparison of measured relative phase (solid circles) with that calculated by the numerical algorithm (open circles) and the desired values (solid line). These data are from the same measurement illustrated in Fig. 5.

These results are typical of all obtained and indicate that the array can generate any desired evanescent wavenumber between the highest determined by the minimum number of stripes per wavelength and the lowest determined by the width of the array. The array is capable of generating this field uniformly over a specified two-dimensional planar surface. The wavenumber spectrum generated is that of a convolution of the desired evanescent wavenumber with that of the aperture. The bandwidth of the main spectral lobe is then entirely a function of the size of the array relative to the evanescent wavelength and can be made as narrow as desired by increasing the size of the array and the number of stripes.

IV. CONCLUSION

A planar array has been described that is capable of generating a desired evanescent wavenumber pressure field over a specified region. The array was found to be capable of uniformities of at least ± 1.0 dB in amplitude over the specified region while generating the desired phase speed. The shading coefficients used in generating the pressure field

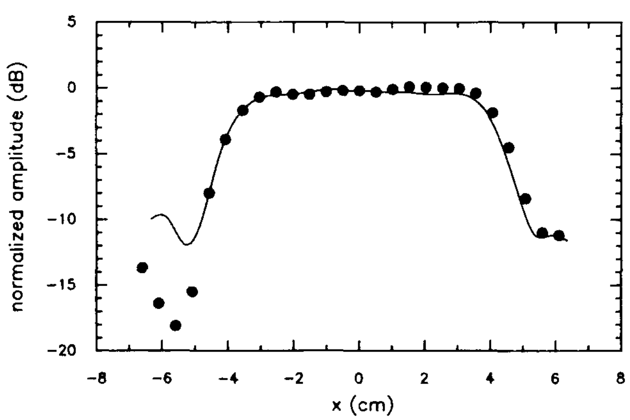

FIG. 5. Comparison of measured pressure amplitude (solid circles) with that calculated by the numerical algorithm (solid line). The data were obtained for the same conditions as that in Fig. 4 except a 7.34-cm-wide window region was used.

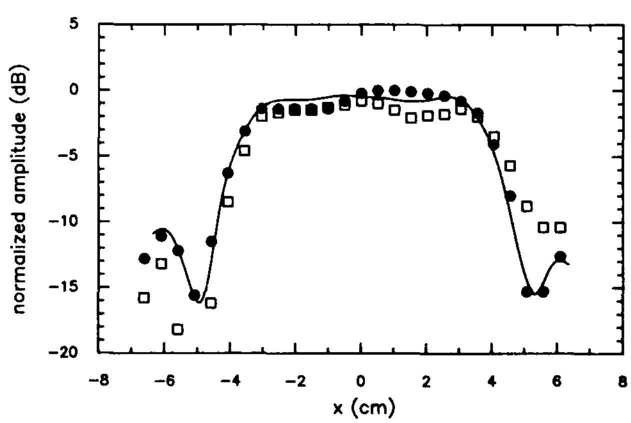

FIG. 7. Comparison of measured pressure amplitude (solid circles) across the centerline of the array ($y = 0$) with that (squares) for $y = 3.2$ cm. The curve is the calculated value across the centerline of the array. Both measurements were obtained at $z = 0.63$ cm while the array was driven at 1 kHz and was generating an evanescent wave with phase speed of 60.2 m/s.

were calculated from a simple-source numerical algorithm that included a constraint setting the acoustic monopole moment equal to zero. It was also found that the window width must be chosen in a manner consistent with the wavenumber spectrum of the convolution of the aperture function with the evanescent wavenumber being zero at the endfire acoustic wavenumber.

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